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A FURTHER AMPLIFICATION OF RADIATION PROTECTION CRITERIA FOR THE EXPOSURE OF MAN TO SPACE RADIATIONS ON MISSIONS OF SHORT DURATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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By

William L. Gill and Stanley C. White, M.D.

SUMMARY

Radiation exposure limits for short duration missions were established to provide criteria for shield design, and in the last year these criteria have received intensive review by many scientific groups. The original limits, however, have not been significantly altered after this intensive scrutiny. The recent discovery of the artificially trapped radiation belts has required the application of these limits for actual flights sooner than anticipated. Previously established dose limits are further amplified and interpretations are provided to aid the shield designers and persons who make operational decisions.

INTRODUCTION

Radiation exposure limits for short missions (ref. 1) were set forth to provide criteria for shield design, and in the last year these criteria have received intensive review by the National Academy of Sciences (ref. 2), the Presidential Scientific Advisory Committee, and by leading members of the radiology and the radiation biology community in numerous informal meetings. The original limits proposed have not been significantly altered after this scrutiny. The recent discovery of the artificially trapped radiation belts has required the application of these limits for actual flights sooner than anticipated. As detailed shielding and operational problems have arisen, it has become obvious that further explanation of the application of these limits, together with some description of the consequences of exceeding the various limits, is required. The purpose of this paper is to amplify further the dose limits previously established and to provide interpretations to aid the shield designers and persons who make operational decisions.

REVIEW

In the establishment of the exposure criteria for the short missions, the following conditions were applied:

1. The philosophy of radiation exposure for early space missions was one of balancing the risk of the deleterious effects of radiation against the other mission risks.

2. In the consideration of this problem for a limited number of personnel, only the somatic effects of radiation were considered; and genetic damage to the population as a whole is considered negligible.

3. For personnel who demonstrate no clinical indications of radiation effects, previous radiation exposure history was ignored in the evaluation of the acute effects of radiation.

4. The mechanisms of chronic space radiation effects are little understood, and it does not appear that the effects of such variables as dose rate, periods between exposure, age at exposure, and total dose can be brought to a single, coherent, quantitative model in any organ or organ system in the near future. Therefore, a conservative approach to this phase of the problem has been applied. The exposure limits during a flying career, which was estimated to be no shorter than 5 years, were the same as the permissible limits over a 30-year period for an atomic industry radiation worker. A flying career was considered to start only after an appreciable dose of radiation had been received, as will be described in a subsequent section. The 30-year limit has not yet been shown to produce deleterious effects, although some minor manifestations of radiation changes may be noted near the end of life.

5. The radiation dose pattern in the body due to isotropically incident corpuscular radiation is very much higher on the surface than at the midline, and the arrangement of equipment in the vicinity of the body can cause considerable variation in this pattern. The body itself considerably attenuates the incident radiation; thus, the effect of radiation exposure is to deliver markedly different doses to different organs or different sites in the same organ systems. This type of exposure is very much different from that delivered by plane monodirectional gamma rays or neutrons, where the dose delivered to all portions of the exposed volume of a body seldom varies by more than a factor of 3. The measure of exposure dose - for example, the incident body dose measured in air - can be correlated with biological effect in the latter case but is meaningless in the isotropic exposure. To evaluate the biological effect for space radiations, the dose at the site of interest must be measured or calculated. Hence, both the dose and the point in the body

where it is measured must be specified in a shield design. The shield designer must describe the pattern of radiation in the case of actual exposure to provide the attending physician with insight as to the possible effects of exposure. With the incorporation of the above factors, table I was prepared for shield design criteria and was considered to cover all the organs which would influence shield design.

TABLE I.- RADIATION EXPOSURE DOSE LIMITS

Critical Organ	Maximum permissible integrated dose, rem	RBE, rem/rad	Average yearly dose, rad	Maximum permissible single acute emergency exposure, rad	Location of dose point
Skin of whole body	1,600	1.4 (approx.)	250	500[a]	0.07-mm depth from surface of cylinder 2 at highest dose-rate point
Blood-forming	270	1.0	55	200	5-cm depth from surface of cylinder 2
Feet, ankles, and hands	4,000	1.4	550	700[b]	0.07-mm depth from surface of cylinder 3 at highest dose point
Eyes	270	2[c]	27	100	3-mm depth from surface on cylinder 1 along eyeline

[a]Based on skin erythema level

[b]Based on skin erythema level but these appendages are believed to be less radiosensitive

[c]Slightly higher RBE assumed since eyes are belived more radiosensitive

APPLICATION OF EXPOSURE LIMITS TO SHIELD DESIGN- OPERATIONS PLANNING, FLIGHT ELIGIBILITY OF ASTRONAUTS, AND OPERATIONAL DECISIONS DURING FLIGHT

Yearly Limits

These limits have been imposed to limit the chronic or delayed effects of radiation. Two reasons are advanced for imposing these limits:

1. The effect of radiation is known to be dose-rate dependent; and the delivery of the dose in several very large increments can produce delayed effects, which may appear within 5 years (shortest flying career) or less.

2. The chronic effects at the conclusion of a flying career may be more severe if the dose is delivered in large increments.

Therefore, for short missions (that is, a duration of about 2 weeks), which must pass through known radiation areas, the dose from this radiation field should not exceed the yearly limits during the mission; and if the weight penalty is not high, should be reduced as much as possible. Either the vehicle shielding design and operational planning should insure that this criterion is met, or the mission trajectory or duration should be modified if the shielding weight penalty cannot be accepted prior to the flight. The only known radiation fields where these criteria may be applied at present are the trapped radiation belts around the earth. The procedure outlined above requires close cooperation and "trade-offs" between personnel engaged in shield design and those engaged in operational planning. It must also be recognized, however, that knowledge of the trapped radiations is far from complete and that uncertainties exist which are difficult to resolve completely by quantitative methods. As a result, flight cases may arise where the yearly dose limits are exceeded. The operational procedure for handling such a situation should be well established and understood prior to the flight. For example, such actions as an unplanned abort may place the astronaut in considerably more jeopardy than an additional dose of a few more rads. The astronaut can receive doses up to the single emergency limit shown in table I if this limit would permit safer landing conditions. The trapped radiation belts do not produce dose rates so high that limited additional time cannot be spent in the radiation area to effect a safer landing or a similar evasive maneuver. In exercising this option, however, the operational commander should attempt to keep the total accumulated dose as far below emergency limits as other operational considerations will permit. The astronaut would not be considered eligible for another mission until his total cumulative dose had dropped below permissible limits. Figures 1 to 4 show the total permissible accumulated absorbed dose to various organs plotted against years of flying career. For purposes of these figures, the flying career commences when an astronaut has accumulated 10 percent of a yearly dose to any organ.

For an astronaut to be eligible to undertake a mission, his exposure record should be such that the sum of previous flight exposure and calculated exposure should not exceed either the exposure limit envelope or the yearly dose. In the event that a dose is delivered in a mission to the extent that the exposure limit envelope is exceeded, the astronaut should be grounded until such a time as he can again meet the criteria set forth in the preceding sentence; and in no case should this period be less than 6 months. This concept applies to eyes and to blood-forming organs. The skin requirements may be waived if the total exposure to date is less than 50 percent of career total.

Emergency Levels of Exposure

With respect to these levels of exposure, the concern is the immediate acute effects of radiation and the performance of the astronaut while still in space. It is expected that there will be observable radiation damage, which will reflect in a decrement of performance of the astronaut. The operations group is interested in how great this decrease in performance may be and in how soon it will appear. The designer should have such information in order to place an upper limit on exposures which may be possible from events which have a remote possibility of occurrence. To establish these limits, the environment, the time of exposure, and the biological effect must be considered. The range of dose and of dose rate will help put the problem of radiation exposure into perspective.

The solar proton event has been considered the gravest radiation hazard which an astronaut will encounter. During the last solar cycle (ref. 3) the total number of particles per cm^2 of energy greater than 30 Mev which intersected the earth has been estimated to be between 10^{10} and 10^{11}. The total dose produced by these particles in a thin-walled, tissue-equivalent chamber in free space has been calculated to be about 5×10^3 rads. The largest event on record produced a dose of about half this magnitude. A typical large flare can be expected to deliver its dose in from 50 to 100 hours. Thus, the free-space dose rates are quite modest and average values have been estimated to range between 7 and 15 rad/hr, depending upon the size and spectrum of a given flare. The maximum free-space dose rate has been calculated to be no greater than 20 rad/hr.

In much of the literature on the calculation of dose and dose rated to date, the calculations have been based on the idealized chamber described above and have been interpreted as typical exposure doses from monodirectional gamma and neutron radiation. As was pointed out previously, the exposure dose is not related to expected biological effect because the body provides considerable self shielding. If the dose to the surface of the body is to be determined, it must be reduced from one-fourth to two-thirds of the free-space chamber value, because of the location of the absorbing tissue in question. (See ref. 1.) Thus, the dose to the skin of an astronaut exposed in free space for an entire solar flare will not exceed 1,600 rads whereas the dose might be as low as 600 rads in deeper tissues. The dose rate he would experience on any surface area of the body would not be expected to exceed a maximum of 14 rad/hr; therefore, he would have considerable time for evasive action. If the astronaut were exposed for the entire duration of the flare without the protection of any shielding, the organs at depths of from 2 to 8 cm in the body (typical of the hematopoietic system) would receive doses from 250 to 30 rads, respectively, depending on their location. The midline dose would probably approach 25 rads.

From the above data, and from the known bilogical effects of radiation, some reasonably cautious estimates of the situation may be extrapolated. In evaluating the acute effects of radiation from an operational standpoint, effects are classified as follows:

1. Immediate effects - those effects which are produced in the first few minutes or hours.

2. Delayed effects - those which appear from a day to a few weeks after exposure, and from which there is complete recovery within a month or more. In figure 5, which illustrates this concept, the steepness of the slope of the initial part of the curve (the immediate effects) and the place at which the degree of fitness reaches a minimum depend upon the total dose received. For prognosis of the degree of severity of the delayed effects, the degree of severity of the immediate effects and the rapidity of their appearance can give considerable insight into the expected delayed effects (ref. 4).

Acute Radiation Effects

In assessing the performance of the astronaut, it is extremely difficult to separate the interplay of various organ systems in the symptoms which may develop after exposure. However, an extrapolation can be attempted from known radiation effects which may provide some insight into this problem.

For a solar flare of very large size, one estimate of the immediate effects is that a dose to the skin of 1,600 rads will produce an erythema. There may be reddening and dryness commencing from 24 to 36 hours after the dose reaches the 800-rad level. Anorexia, nausea, and vomiting, using gamma radiation of short duration has been observed at about 200 rads to all organs. If the assumption is made that these effects with gamma radiation can be associated with organs located from 2-cm to 8-cm depth, then it can be estimated that the dose from a solar proton event will be 250 rads at 2-cm depth, 30 rads at 8-cm depth, while the midline of the torso of a man would receive around 25 rads. Since it will take about 2 days or more to deliver this solar proton dose, it is estimated that there is little possibility of these symptoms appearing until from 3 to 4 days after flare commencement, if at all. Forecasted symptoms would be slight nausea and anxiety as the worst estimate of this situation. Diarrhea would not appear to be a problem as an immediate effect (neither the Oak Ridge nor the Yugoslav patients developed this symptom). See references 5 and 6.

In summary, during the very large flare, the only possible immediate symptoms which could appear are anxiety, nausea, and anorexia. Erythema and conjunctivitis could develop during the fourth day of the flare or the day following. In arriving at this analysis of symptoms, it is assumed that the astronaut is in free space during a flare in which particles less than 30 Mev were not used in the calculation. In the vehicle with normal construction none of these symptoms should appear.

Delayed Radiation Effects

Consideration should be given to the delayed effects which may be expected and the seriousness of these effects. On earth, if a person is exposed to radiation, there are clinical indices which give considerable insight into expected delayed effects in the range of interest, such as white blood cell counts, platelet counts, mitotic index of bone marrow, and body temperature. By considering these indices, a simplified model of the physiological effects after exposure to space radiation may be constructed. The general steps which are followed in the development of the delayed effects are discussed as follows.

Figure 6 illustrates the sources of changes in the maintenance tissue tone. In this generalized model the first source of tissue damage is the direct action of the radiation itself. There will be an almost immediate reaction as cells are killed by the radiation, and this effect will continue for a considerable period of time because part of the damage does not become apparent until mitosis (cell division) is complete. Both the inhibition of mitosis by irradiation (ref. 7) and the differences in normal mitotic activity influence the time of appearance and severity of degenerative changes in tissue. It may be estimated that these types of tissue degeneration occur in the first week after exposure.

A second source of tissue degeneration which commences as the direct immediate acute radiation damage progresses is the disturbance of the endothelial and vascular tissue supplying the irradiated tissue (ref. 8). The irradiated tissue may thus suffer from both hypoxia and lack of nutrition. This constriction of the blood-supplying capillaries will also prevent phagocytes in the blood from performing their debridement action in the affected tissue. The negative findings concerning bacilli on stomatitis and shallow ulcers from the 7th to 15th days in the Lockport incident (ref. 5) are suggestive of this mechanism, as is the respiratory system inflammation so often noted in the treatment of patients by radiologists (ref. 8). If the tissue which has been irradiated breaks down in such a fashion as to permit bacteria to invade it, a third source of tissue degeneration is introduced. Throat infections noted in the Oak Ridge patients (ref. 5) are evidence of the operation of this mechanism.

A third source of tissue damage, or inhibition of tissue recovery in the case of extensive body irradiation, is the loss of leucocytes and lymphocytes from the blood. The degree of depression of the former is directly related to the bone marrow dose. The latter is more closely related to the total gram-rad dose or total energy absorbed by the body. The depression of these components in the peripheral blood may be interpreted as a dilution of the components in the peripheral blood, which together with a constricted vascular system and damaged endothelial system, promotes the further degeneration of the tissue under examination.

The clinical evidence of this condition can be seen from the white blood cell counts. The measurements within a day of the time of irradiation can be detected at 50 rads and will indicate, for doses around 200 rads, a dramatic shift in values. There may be a rise in lymphocytes the first day or so after irradiation with gamma rays, followed by a rapid fall. On about the fifth day the minimum count is reached, and gradual recovery over the next few months restores the lymphocytes to near preexposure value. Since the entire lymphatic system is not completely exposed under space radiation conditions, further investigation of this phenomenon should be made. Conceivably, this symptom may be absent or not as severe in space radiation exposure.

The injury to bone marrow cells accounts for most of the decrease in white blood counts with gamma radiation after the fifth day, reaching their minimum values around the 25th to 30th day. The neutrophils appear to be the component of the white blood cells accounting for this decrease, and monocytes may actually increase. The change in neutrophils is associated with the damage which the bone marrow has suffered. The study of bone marrow damage is one in which further research is required. A local dose of 600 to 800 rads should be capable of producing aplastic marrow. The decrement in performance of unit volumes, of bone marrow at doses from 0 to 800 rads, has not been quantitatively examined. The speculation that the gram-rad dose below 800 rads can be a measure of performance decrement of this organ system is heuristic. The gram rad is a measure of the total energy deposited in the organ in question and is defined as

$$G = \int_{\text{all organ } V} D(\rho V)\, \rho dV$$

where

G gram rad dose

D dose, rad

ρ density, g/cm^3

V volume of the organ system in question, cm^3

This effect is not expected to be as severe for space radiations as has been previously observed in whole body irradiation.

The final delayed effect which may manifest itself is the appearance of petechiae in heavily irradiated areas, and possibly in areas which have not received a heavy dose. This phenomenon is related to the drop in the number of platelets, and commonly occurs when the total platelet count decreases by a factor of 10 or more from preirradiation values. This phenomenon usually occurs somewhere between the 22nd and the 37th day after irradiation.

Where clinical observation is feasible, it is therefore obvious that the complete white blood count and platelet counts, when taken at periodic intervals, can provide valuable insight into the recovery of astronauts exposed to space radiations. The other diagnostic tool for evaluation of the hematopoietic system is to measure the mitotic index of the bone marrow which may provide some insight to the damage which that organ system has received.

A nonspecific symptom which appears very frequently acute radiation exposures is a feeling of weakness which persists for a long period after the exposure. There are two sources which may contribute to this symptom:

1. A depression in the red blood cells. This symptom is slow to develop. Initial changes may not show until about the 20th day after exposure, and the minimum value will not be attained until the 35th to 45th day. The long term symptoms of fatigue may be associated with this depression.

2. The second source of weakness in whole body exposure may be associated with creatine metabolism, or with beta-aminoisobutyric acid levels in the urine. Since creatine is closely associated with muscle contracture, the creatine-creatinine ratio may be associated with the fatigue reported in patients. The work at the University of Rochester (ref. 5) indicates that this effect should be closely followed.

Damage to Specific Organs

Eyes.- In an acute radiation exposure where the eye is protected by only a few millimeters of plastic, it is conceivable that a dose of 1,000 rads might be delivered to the corneal epithelium. The immediate acute effects would appear to be negligible, although there may be some conjunctivitis. Previous investigators (ref. 9) have shown that pyknosis of rods appears in cases of exposure of from 1,000 to 2,500 rads. The latent period was about 5 hours. It is estimated that below 2,000 rads the possibility of this occurrence is not high. A moderately thick visor should reduce the dose to below 100 rads, and in this range there would appear to be little evidence of immediate acute eye damage. However, it should be recognized that the delayed effects of this eye exposure are not well documented. In the Vinca Zero-Energy Reactor accident, facial erythema and conjunctivitis were noted at doses in the 400- to 640-rad range about 8 to 10 hours after the accident (ref. 5). The lower dose rates in space will probably not produce such an effect since the total dose will be delivered over a period of 2 to 4 days; hence, it might be postulated that such an effect would appear in the third to fifth day. These effects inspire some heuristic arguments for further investigation of synergism of radiation and vibration during reentry. It is to be expected that delayed effects of radiation may develop. The Lockport incident disturbances of retinal function as late as 210 days after exposure in the most heavily irradiated victim were noted (ref. 5). The exposure in this case is not well established, but is estimated to be between 1,200 and 1,500 rads. The clinical picture of the Oak Ridge Y-12 and the Yugoslav exposures indicates that eyes showed delayed symptoms, for example, conjunctivitis in the 200- to 650-rad range. Eighteen months after the Y-12 incident one man showed abnormalities, particularly peripheral punctuate densities in the lens chiefly in the posterior subcapsular and cortical regions. The Yugoslav victims, in the range from 420 to 600 rads at 17 weeks, showed very slight subcapsular cloudiness at the back of the lens, spreading in star formation to the periphery (ref. 5). This condition had cleared in all but one patient by 7 months, and at 18 months all had normal findings. The problem in this delayed effect could conceivably be from either vascular disturbances or change in components of the peripheral blood which requires further investigation.

The limited data on chronic effects of radiation of the eye (ref. 10) would indicate that a 50-percent probability point for developing cataracts is 200 rads in a single short treatment. For treatments with gamma radiation extending from 3 weeks to 3 months, the dose must be increased to 400 rads to produce a similar effect. Thus, exceeding the limit for emergency exposure shown in table I, could conceivably ground an astronaut because of loss of visual acuity. This problem, however, can be avoided by conservative eyeshield design, which would not involve a major weight penalty.

Skin.- A detailed discussion of the effects of radiation on the skin may be found in references 8 and 11. The lowest level for an effect of radiation is probably characteristic to 1,200 rads. At this level of irradiation an immediate redness of the skin will be produced. This redness will be followed by pigmentation, which may remain, and dryness in the first 10 days. There may be several waves of redness. About 8 to 10 days after exposure epilation will occur, which will require up to 2 months to repair.

If the dose administered to the skin is somewhere between 1,200 to 1,500 rads, the waves of erythema may occur more often and there may be slight edema. The restoration of hair is slower and may require several months.

At 2,500 rads, total necrosis of the skin occurs in 1 to 8 hours. The skin appears inflamed and then apparently recovers, with a reappearance at from 8 to 12 days. After about 12 days, the skin blisters and commences to slough off. The appearance is ulcerous and may have a gangrenous appearance. The appearance of these symptoms, of course, assumes that the radiation is not penetrating, since at this level death would probably occur before all the symptoms previously described develop. It is possible that muscle or other deeper layers of the tissue below the dermal layer may be involved. Healing may be slow and take many months.

The problem in space travel should then be obvious. The immediate reddening of the skin of the occupants of smaller space vehicles can be estimated as serious, since there will be little opportunity for personal cleanliness. The problem of secondary infection from skin bacteria may be serious if missions are extended beyond a week after irradiation. The continuation of a mission in which a space suit must be worn does not appear possible if the dose exceeds 1,000 rads. However, this condition should never arise if shielding has been properly designed. The appearance of petechiae at 20 to 30 days should seldom be noted unless there has been extensive damage to the hematopoietic system.

Respiratory system. - The deposited dose to the lungs that will produce damage is estimated to be 800 to 1,000 rads. Even at this level there is little or no evidence of damage until between the 7th to 15th day. The average shielding to the lungs should reduce the dose to around 200 rads in free space, which at normal pressures, temperatures, and air composition should produce no clinical effects. The ability of oxygen to intensify radiation damage at cellular level has been documented. In the treatment of patients in the third and fourth weeks, the damage of the upper mucosa and the reflex-atelectatic pneumonias have been extremely well documented. Some synergistic effects which may require further investigation might possibly exist in this organ system because of the physiological stresses such as a pure oxygen atmosphere, reduced pressure, and reentry gravitational forces. Overall, however, this organ system does not appear to present a serious hazard.

Bone. - To date, all the emphasis on bone has centered around the hematopoietic system. Since bone containing this tissue is relatively deep in the body, any single exposure on a 2-week mission will produce little effect to the hematopoietic system containing bone itself. Of much more interest from a space medicine standpoint may be the exposure of bone which is not protected by a few cm of tissue, particularly if fractures occur. There are a few references in the literature to this phenomenon (refs. 7, 12, and 13). Some problem may exist with the healing of fractures, and cumulative damage may be pronounced in this area because of vascular changes. A single acute dose in excess of 400 rads is estimated as a threshold for this effect. This area, too, is one which requires further study, particularly the chronic effects of fractionated doses.

Hearing. - The hearing system has been almost completely neglected in the literature. Since paralysis of the villi and cilia have been noted in other organs because of radiation damage, it would appear conceivable that radiation damage to the ear may produce partial paralysis of parts of the vestibular apparatus and may be the source of nausea and vomiting in the acute radiation syndrome. A partial check of the literature has produced no information on this subject. Since there has been considerable concern on the effects of weightlessness on vestibular function, there would appear to be a need for further investigation in this area. There should not be a high dose to the semicircular canals, since they are located about 3 to 4 cm from the surface of the body. The dose should be below 100 rads.

Oral and nasal region. - The general picture which has been drawn for the skin would also appear applicable to the mouth and nose. The threshold for damage is probably in the 500-rad range which is possible with space radiations. In about 4 to 6 days necrotic plaques on gums and stomatitis might be expected as the worst case and some gingivitis in the less severe cases. The appearance of tonsillitis and pharyngitis between the 13th to 30 days, which is associated with doses around 300 rads, might be quite serious because of secondary infection on a long mission, but should have little bearing on missions of 2 weeks' duration. Recurrence may be expected between 25 and 35 days if the hematopoietic system has been irradiated in excess of 200 rads.

Digestive tract. - The abdominal area is protected by a minimum of 1 to 2 cm of soft tissue. It has been calculated that areas of the digestive tract 1 cm deep should receive a dose of 500 rads while the areas 2 cm deep should receive 200 rads if an astronaut is in free space during a solar flare. If the entire intestinal area is irradiated to the 400-rad level, persistent and diffuse pains in the abdomen are noted; the entire colon becomes sensitive, and some disturbance of peristalsis may be expected. At 200 rads little or no symptoms should be noted. Therefore, it is concluded that the gastrointestinal tract might not appear to be seriously affected by a major solar event even when the astronaut is in free space.

Testes. - The gonads are partially protected from the isotropic protons of a solar flare by the lower abdomen and the thighs. The abdomen and thighs have been estimated to be equivalent in shielding from 3 to 6 grams per cm^2. A dose from a flare of 500 rads to the skin could very easily result in a dose less than 100 rads to a point in the center of the testes. Doses of 100 rads can induce some transitory decrease in sperm count and a diminuation in fertility. Although the testes are relatively radio sensitive, their recovery has been shown to be almost complete with time. Permanent sterility requires doses as large as the LD_{50} level of 500 rads.

No hormonal changes have been seen in man with doses of 100 rads to the testes. The genetic changes are possible with low levels of radiation. With a probability of exposure to a solar flare of 0.01, a low probability of siring a child, and the self-shielding of the capsule thighs and abdomen, the genetic risk for a short mission is not of major significance.

CONCLUDING REMARKS

From the description of the radiation effects of a major solar flare, as described for various organs and organ systems, it is obvious that there is no immediate effect which is completely incapacitating. A total incapacitation which occurs immediately is usually associated with doses to the central nervous system of 5,000 to 10,000 rads. A dose received in free space might produce an early nausea and anorexia and a severe skin inflammation and infection about a week after exposure. It does not appear that an individual will ever receive a dose producing these effects and the total effect may be considerably less for the following reasons:

1. Dose rates to the skin in free space are moderate even at the maximum of the event (approximately 20 rad/hr).

2. Duration of the event is long (more than 50 hours), and it appears unlikely that a space suit will be designed to sustain life for this long period.

3. Considerable reduction in the dose is achieved with even modest shielding.

The space vehicle is probably adequate to reduce all dose levels to tolerance.

The delayed effects from radiation from a solar proton event appear to need further study; but in general the total dose received by any single organ does not appear likely to produce severe symptoms, and with the intrinsic shielding of the vehicle, the physiological effects should be minimal or absent.

The chronic effects which are controlled by the setting of yearly limits, may, in the long run, be the limiting factor for the astronauts exposed to space radiation.

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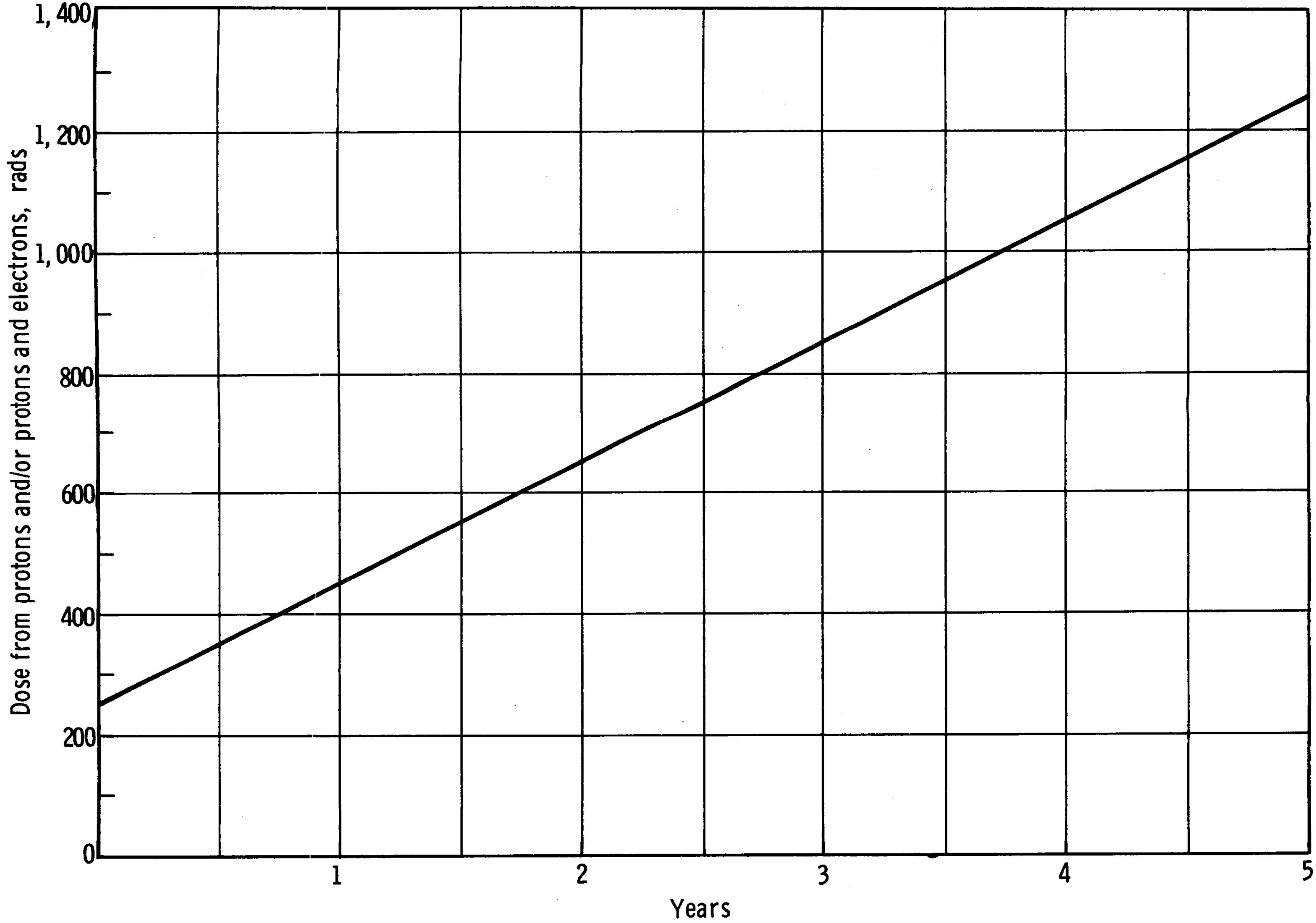

Figure 1. - Permissible skin exposure (single acute exposure, maximum, 500 rads).

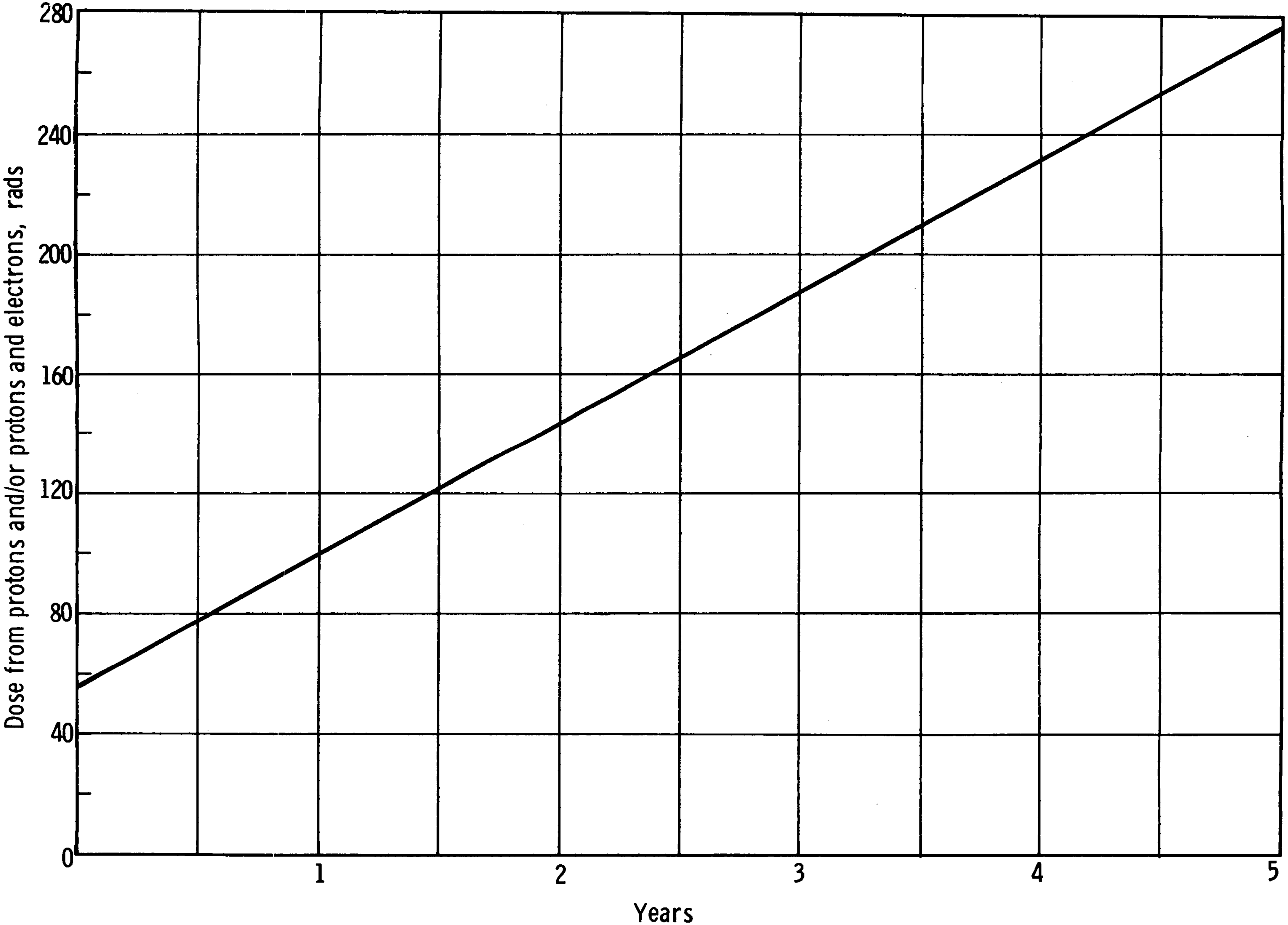

Figure 2. - Permissible blood-forming organ exposure (single acute exposure, maximum, 200 rads).

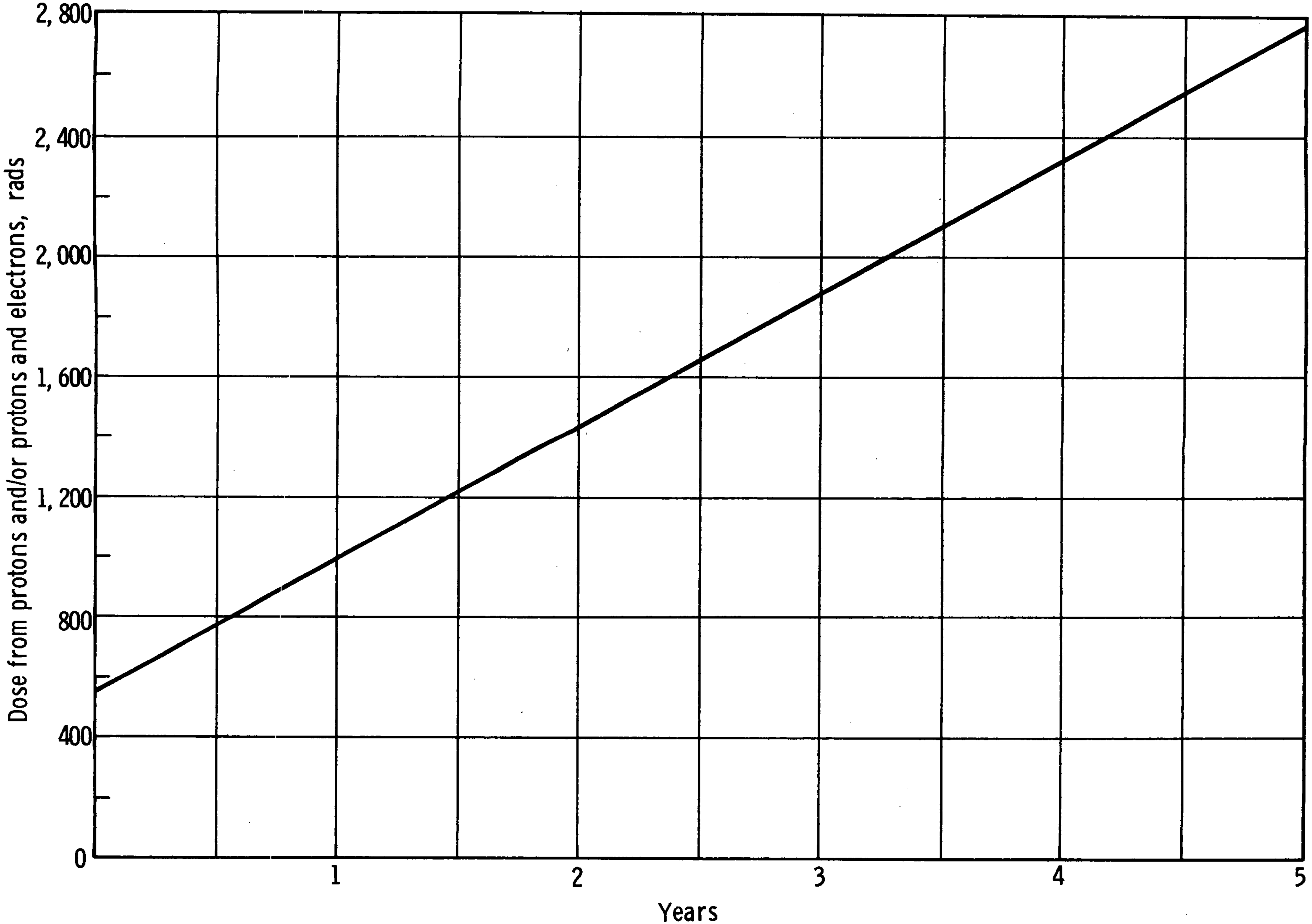

Figure 3. - Permissible foot, ankle, and hand exposure (single acute exposure, maximum, 700 rads).

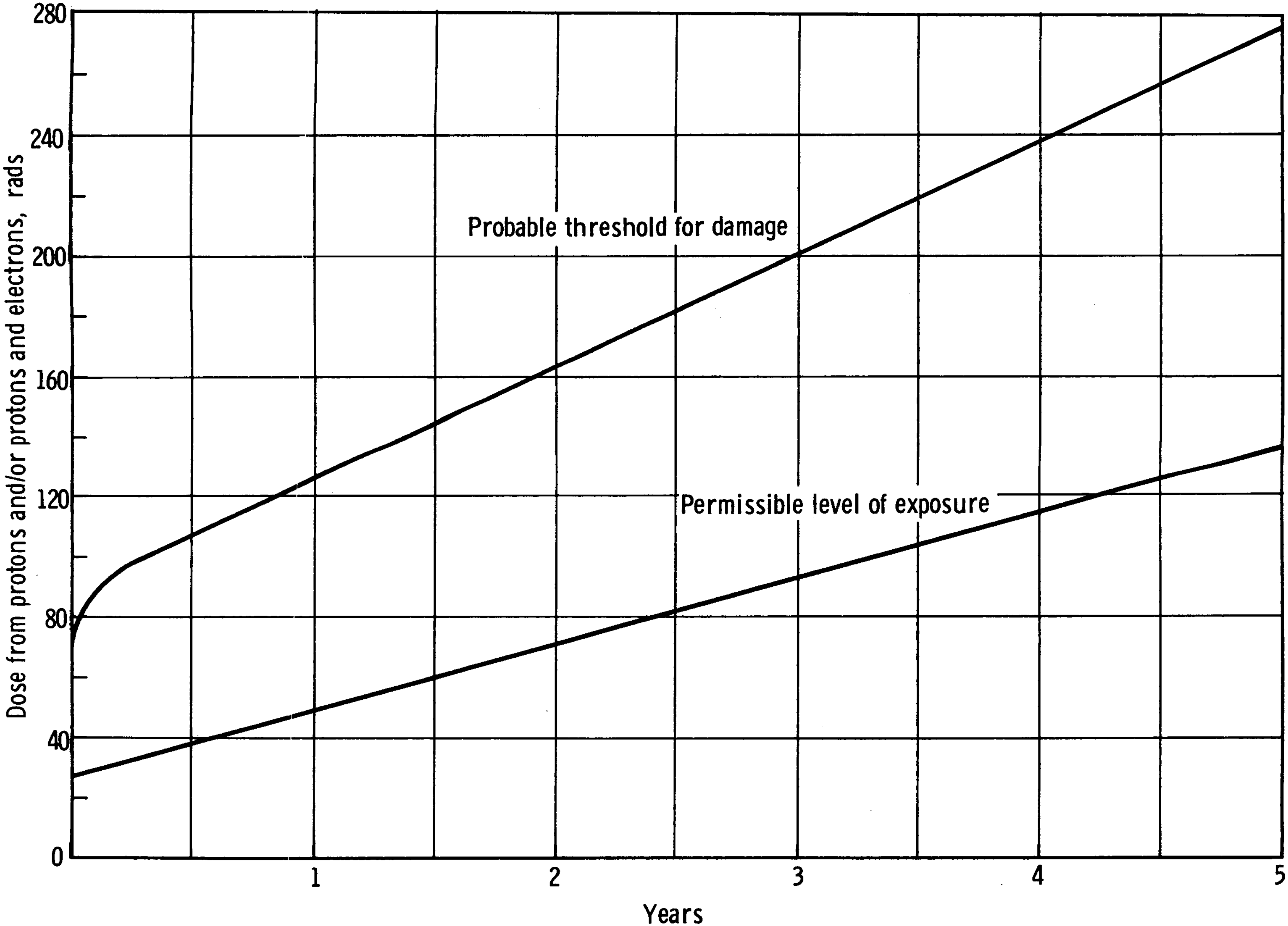

Figure 4. - Permissible eye exposure (single acute exposure, maximum, 100 rads).

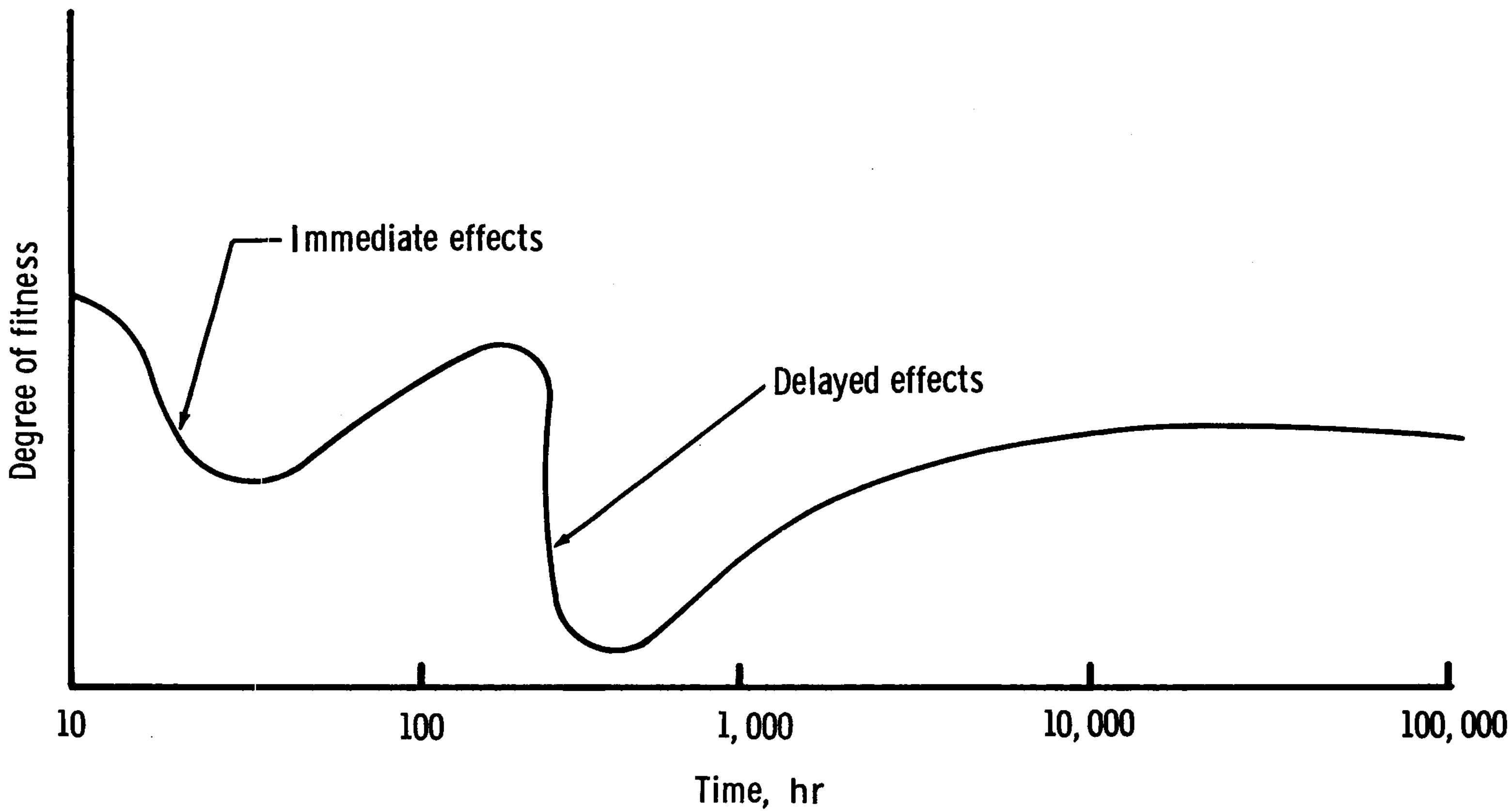

Figure 5. - Physiological effects of radiation.

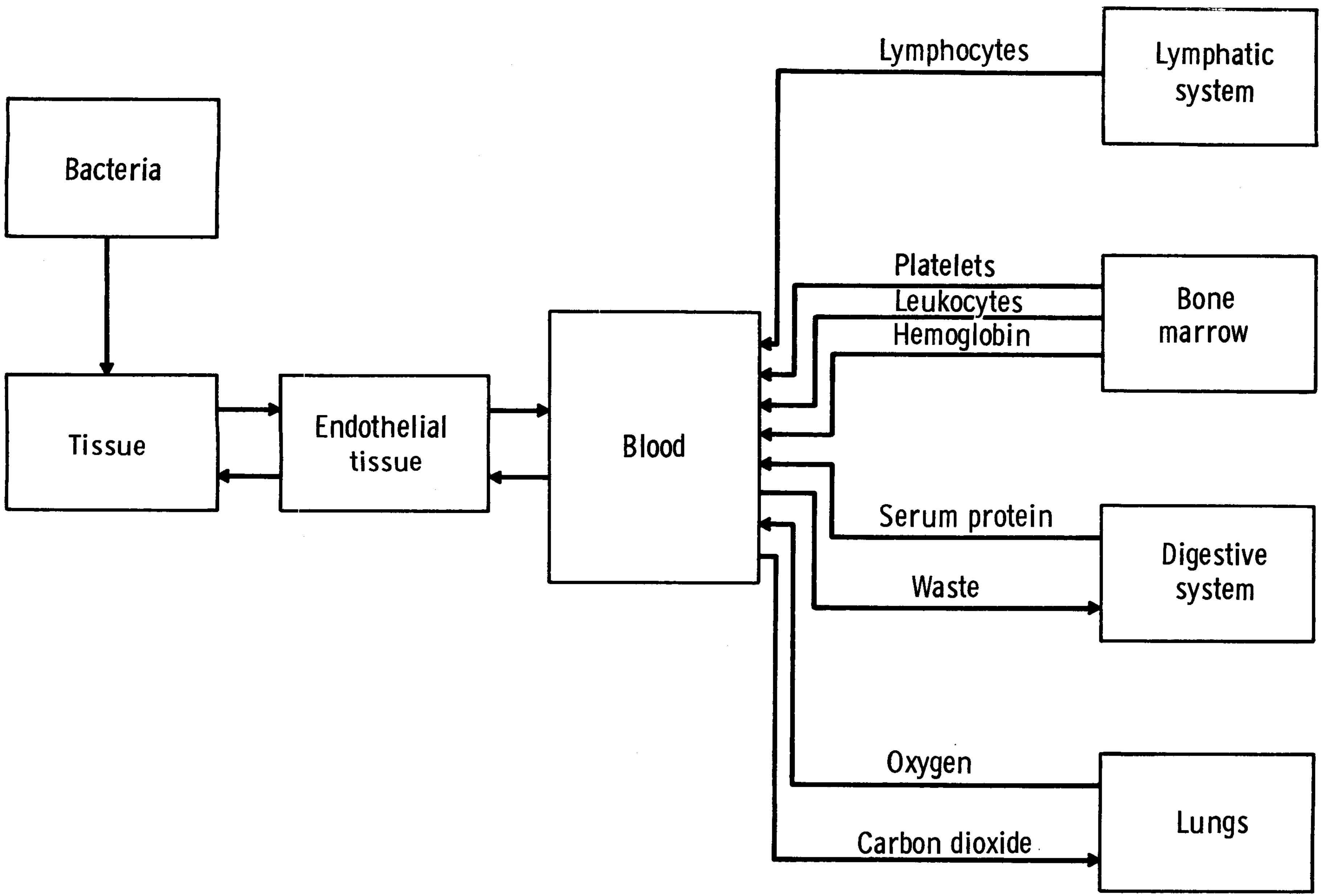

Figure 6. - Simplified model for establishing radiation effects